Renewable and Sustainable Energy Reviews 30 (2014) 490–503

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Categorization of residential electricity consumption as a basis for the assessment of the impacts of demand response actions

Ana Soares *, Álvaro Gomes, Carlos Henggeler Antunes

University of Coimbra/INESC Coimbra, Rua Antero de Quental, No 199, 3000-033 Coimbra, Portugal

A R T I C L E   I N F O

Article history:
Received 27 May 2013
Received in revised form
24 September 2013
Accepted 19 October 2013
Available online 15 November 2013

Keywords:
Residential electricity consumption
Integrated energy management systems
Load diagram impact
Smart demand response
Categorization of responsive demand

A B S T R A C T

In a smart(er) grid context, the existence of dynamic tariffs and bidirectional communications will simultaneously allow and require an active role from the end-user concerning electricity management. However, the residential end-user will not be always available to manage energy resources and decide, based on price signals and preferences/needs, the best response actions to implement or the best usage of the electricity produced locally. Therefore, energy management systems are required to monitor consumption/generation/storage and to make the best decisions according to input signals and the user's needs and preferences. The design of adequate algorithms to be implemented in those systems require the prior characterization of domestic electricity demand and categorization of loads, according to availability, typical usage patterns, working cycles and technical constraints. Automated demand response actions must be tailored and chosen according to this previous analysis of load characteristics. In this paper, a characterization of household electricity consumption is presented and an operational categorization of end-use loads is proposed. The existing potential for demand response to a diversified set of management actions is described and a tool to assess the impact of implementing several actions with different rates of penetration of energy management systems is presented. The results obtained show the potential savings for the end-user and expected changes in the load diagram with a decrease of the aggregated peak electricity demand and a smoothed valley.

Contents

1. Introduction

The increasing penetration of micro-generation has been changing the traditional role of end-users in the residential sector.

* Corresponding author. Tel.: +351 239 851040; fax: +351 239 824692.
E-mail address: argsoares@inescc.pt (A. Soares).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.10.019

Several end-users are now not only electricity consumers but also producers and this trend is likely to increase [1]. At the same time, new types of loads are emerging, namely electric vehicles. Their expected dissemination among the residential end-users will expectedly induce significant changes in the domestic demand patterns and create new challenges to the low voltage distribution infrastructure [2–5].

On the other hand, the supply-side is also facing some changes: smart embedded systems that combine instrumentation, analytics and control are turning the traditional grid into a more efficient self-diagnosing, self-healing, distributed and bidirectional grid [6,7]. This “smart(er)” grid would further benefit of a more active role from the end-user side if he/she is able to respond to external input signals (e.g. dynamic tariffs) by adequately managing his/her electricity consumption and/or by taking the maximum advantage from micro-generation and storage systems.

From the end-user's point of view, demand response plays a key role by allowing a more efficient and integrated management of resources possibly contributing for reducing the electricity bill. From the power system side, responsive demand will allow an improved management of the grid, mitigating the variability associated with renewable generation and reducing the potential undesirable impacts of electric vehicle charging, for instance the creation of a high local peak demand, besides contributing for an improved load factor, lower losses and increased reliability [8,9].

However, the residential end-user is not always available to manually manage in an optimized way, his/her electricity consumption/production/storage in real-time day by day and hour by hour. There are several decisions that must be done that the end-user is neither prepared nor available to deal with, namely:

- the best scheduling for appliances to be turned on/off (washing machines, clothes dryers, etc.);
- the changes in the thermostats setting points and/or the curtailments to be applied over thermostatically controlled loads, such as air conditioners and electric water heaters or even refrigerators and freezers;
- what to do with the energy produced locally (store/use/sell back to the grid);
- how to manage electricity storage devices.

The aim of this paper is twofold. Firstly, it aims at characterizing and classifying in a detailed way the potentially controllable demand in the residential sector in Portugal, namely the electricity demand originated from:

- washing machines, clothes dryer, dishwashers;
- cold appliances and electric water heaters;
- air conditioning systems.

This analysis provides the foundations for the design of diversified management actions to be implemented over the several types of loads.

Secondly, it aims at assessing the impacts of implementing distinct Automated Demand Response (ADR) actions over some of the controllable end-use loads previously identified. These ADR actions might be carried out by Energy Management Systems (EMS) able to optimally manage the end-user's available energy resources.

A brief description of electricity consumption patterns in Portugal is done in Section 2. The demand characterization and load categorization in face of ADR actions is made in Sections 3 and 4, respectively. These two sections allow for the selection of ADR actions to be used in Section 5. The impact assessment of ADR implementation on the load diagram is presented in Section 5 and the importance of EMS is presented in Section 6. Conclusions are drawn in Section 7.

2. Electricity consumption in Portugal

Electricity consumption in the residential sector in Portugal has been increasing steadily and since 1990 electricity consumption has been rising faster than Gross Domestic Product (GDP) per capita. One of the reasons pointed out for explaining this trend is the increasing rate of ownership of electrical appliances associated with higher living standards [10,11].

Concerning electricity generation, Portugal has been doing remarkable efforts in the deployment of generation from renewable sources with the main aim to reduce the need of fossil fuel imports and therefore external energy dependence [12]. Nevertheless, a significant part of the electricity produced in Portugal is based on fossil fuels. Concerning renewable sources, their contribution has been increasing although it is quite variable and mostly strongly dependent on weather conditions. It is therefore important to be able to deal with the variability associated with each one of these resources in order to maximize their integration into the grid [13].

One of the ways to achieve this aim is the application of demand-side management (DSM) actions [14–17]. However, it is important to have beforehand an adequate knowledge of the disaggregated electricity consumption in the residential sector as well as the typical patterns of usage of the appliances that can be somehow controlled in order to choose the best DSM actions [18]. Technical constraints and end-user's preferences that may frame the way loads can be controlled also play an important role that should be considered. Besides contributing for a more efficient operation of power systems and allowing higher penetration of renewables, smart ADR actions may also contribute for reducing end-user's electricity bills and/or increasing the supplier's profits from selling electricity.

Taking into account the load profile of the residential sector disaggregated by end-uses [19] (Fig. 1), it is possible to analyze and to estimate the contribution of end-use loads to the total electricity consumption and electricity bill (Fig. 2).

The regular time of usage gives information about residential end-users' habits and the potential of using some of the appliances in different schedules. Studies about users' willingness to change behavior concerning the utilization of energy services have already been developed [20–23].

3. Controllable demand characterization

The evolution of Electrical Energy Systems towards Smart Grids is expected to provide the residential end-user with the technological basis and the economic incentives to adequately manage his/her energy resources, including local generation and/or

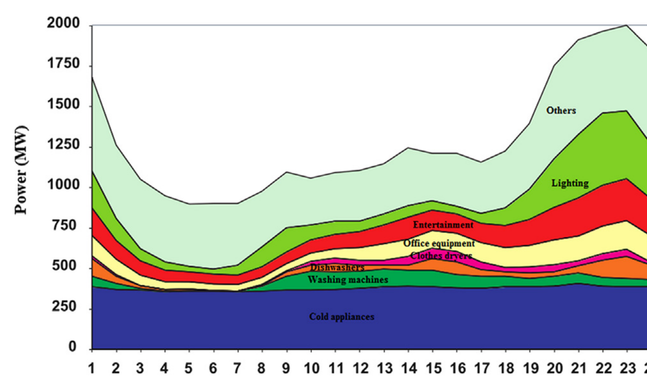


Fig. 1. Load profile of the residential sector [19].

cogeneration, electricity buying from or selling to the grid, stored energy and controllable demand. The smart grid technologies are therefore enablers for the integrated management of resources [24,25].

From the end-user's point of view and in order to minimize his/her electricity bill without reducing comfort or depreciating the quality of the energy service provided, this management must take advantage from the usage flexibility of some end-use loads. This flexibility depends on habits but also on the end-user's willingness to let an automated system control his/her consumption [26].

From the supply side there are also advantages associated with the management of residential energy resources: treating demand as a manageable resource may contribute to postponing or avoiding the investment to increase the system capacity, allowing a better and increasing integration of renewables, reducing peak demand and the operation of less efficient peaking plants [9,16,27]. Other advantages include the increase of the power system's reliability and the mitigation of power market, since in this scenario end-users will have a more active role concerning electricity management therefore influencing kWh prices. The tool developed to assess the impacts of implementing ADR actions presented in this work clearly displays the changes in the demand pattern, namely in the peak demand.

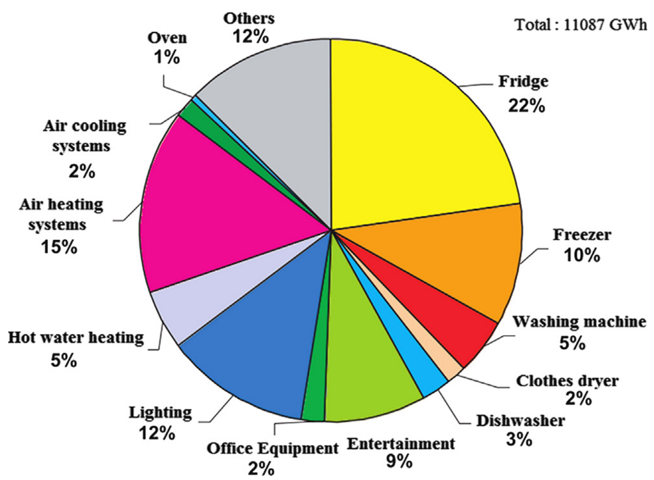


Fig. 2. Disaggregated electricity consumption in the residential sector in Portugal [19].

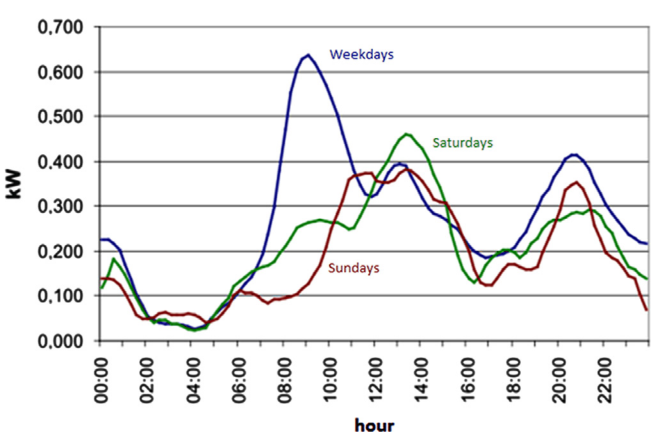


Fig. 3. Daily average consumption of electric water heaters of representative consumers [30].

The following sub-sections will focus on the characterization of controllable loads that might be the target of those management actions, namely regarding their contribution to the annual residential electricity consumption in Portugal, typical working cycles and average daily pattern of use.

3.1. Electric water heating

Electric water heaters represent more than 5% of the annual residential electricity demand in Portugal [19] and their electricity consumption is strongly dependent not only on the routines and habits but also on the number of people using them and hence the amount of hot water used.

In this type of load there is some dissociation between the period during which electricity is used to heat water and the use of hot water. Under a scenario of dynamic pricing it is therefore possible to reduce costs taking advantage from variable electricity prices by postponing/delaying the working cycle or even interrupting it for short periods of time [28,29]. It is also possible to redefine thermostats settings by lowering them when the electricity price is higher and increasing them when the price is lower or when electricity is being produced locally, without noticeable degradation of the quality of the energy service.

Fig. 3 displays the typical daily average electricity consumption of electric water heaters whose data was gathered in energy audits for weekdays, Saturdays and Sundays. Typically, the peaks are found in the early morning and evening for weekdays and, with peaks not so high, a bit later in the morning and in the evening for the weekend.

3.2. Cold appliances

Cold appliances are present in almost every household, sometimes even more than one per house, and are responsible for more than 30% of the annual residential electricity consumption in Portugal (Fig. 2).

This type of load has a working cycle controlled by a thermostat (Fig. 4) and can have the thermostat settings changed or even be the target of short interruptions without worsening the quality of the energy service provided as they can act as energy storage devices [31]. In practical terms, a difference of 1 or 2 °C is not, in general, problematic for conserving food while for electricity

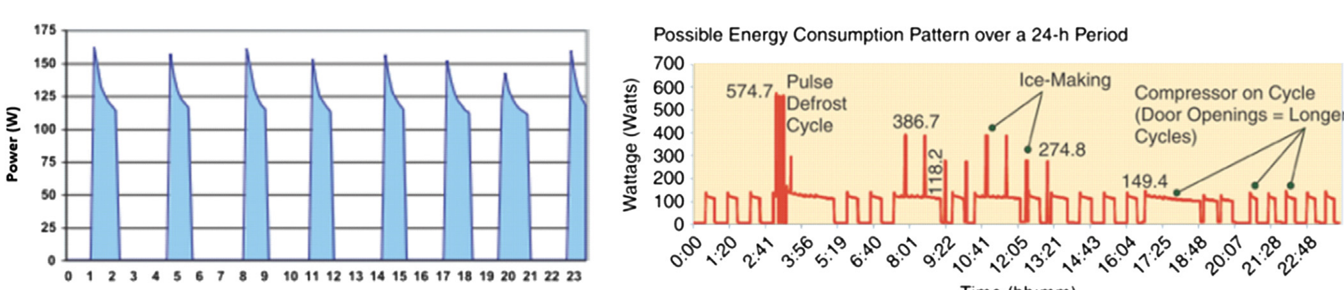


Fig. 4. Typical working cycle of a refrigerator [19,35].

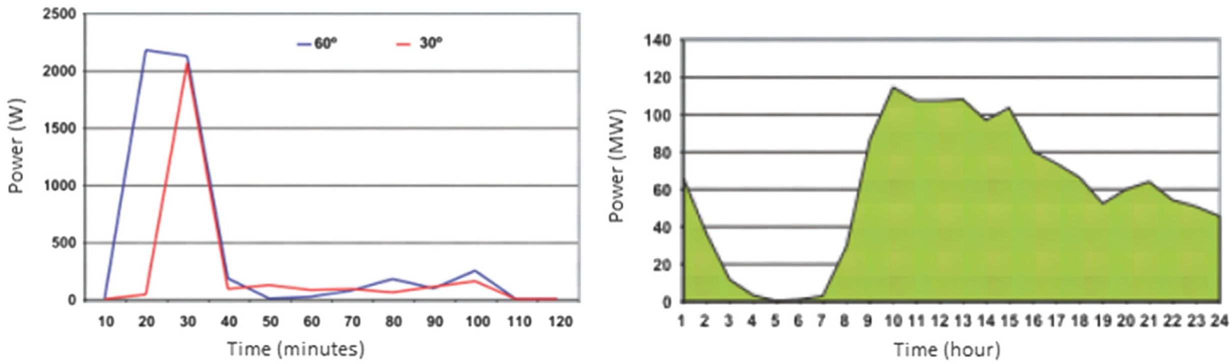


Fig. 5. Typical working cycle of a washing machine and average daily pattern of use [19].

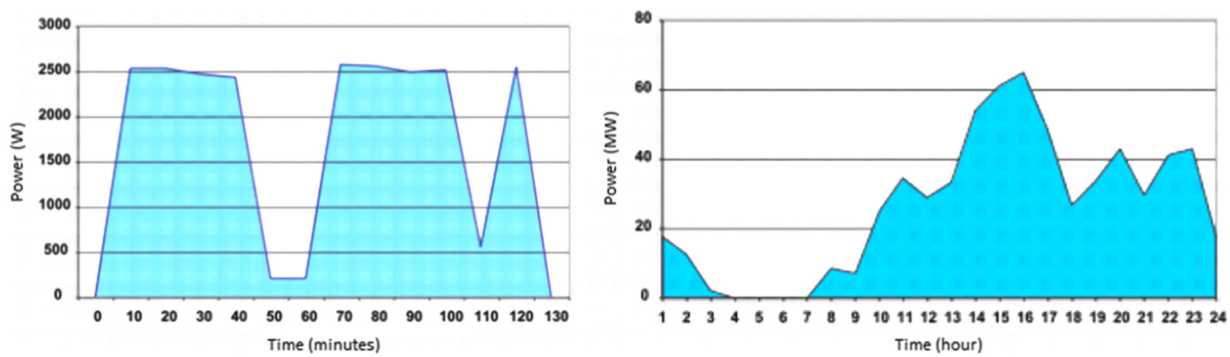


Fig. 6. Typical working cycle of a clothes dryer and average daily pattern of use [19].

consumption it represents a non-negligible difference [32]. Therefore, small changes of the thermostat settings and short time interruptions with consequent small changes of temperature parameters are possible [33,34].

Although one may argue that the power drawn from the power system by cold appliances is relatively low, the fact that they are working all day long in almost every house, meaning the overall energy consumed may be high, along with their storage characteristics, makes them an attractive load to be controlled. This control, either re-set of thermostat parameters or short time interruptions, should not originate temperature variations that may cause the degradation of the quality of the energy service provided, being therefore important to establish the adequate management actions.

3.3. Washing machines

Fig. 5 shows energy use during a typical operating cycle for a domestic washing machine at two different washing programs and the average pattern of use in Portugal. This type of load is mainly put into service in the morning and after lunch period. The information of load usage together with the characteristics of these loads makes them suitable for postponement or anticipation actions. In terms of energy consumption, most electricity is consumed in the water heating phase, being therefore advisable to use low temperature programs.

3.4. Clothes dryer

Fig. 6 provides information about energy and time of use for residential clothes dryers. As for the washing machines, clothes dryers also offer a very significant opportunity to reduce the peak electricity use and shift that consumption to other period of the day. However, it is important to highlight that usually these loads are operated after the working cycle of the washing machine is over, which will for certain have influence on the time shifting window.

Although the ownership rate of these appliances is not very high in Portugal (around 18%), the possibility of controlling them without causing discomfort to the end-user is easily achieved either by shifting the consumption or even interrupting it to take advantage from the residual heat. From an end-user perspective and since the clothes dryer cycle time and energy consumption are linearly related, the interruption of the cycle will not affect drying performance, but will lengthen the duration of the total working cycle by increasing the time that the heater is shut off [35].

3.5. Dishwashers

In Fig. 7 it can be seen that dishwashers are usually used after meals, being ideal to be managed since their electricity consumption can be deferred without bringing discomfort to the end-user as long as the dishes are washed and dried at a stipulated time. Normally the peak of use of this type of loads occurs after dinner, being coincident with peak electricity demand at the residential sector (Fig. 1). If these loads are used when the price of electricity is lower, induced by dynamic tariffs, then economic advantages from using these appliances at the adequate schedule are expected.

Also, along with the possibility to defer the operating cycle, there can also be a power and energy reduction by eliminating the heated drying portion of the cycle pointed out in Fig. 7 [35].

3.6. Air conditioning

Electric air heating and air cooling systems are responsible for more than 15% of the annual electricity consumption in the residential sector in Portugal (Fig. 2). However, the ownership rate of air conditioning systems in Portugal is still not too significant although it has been increasing [11].

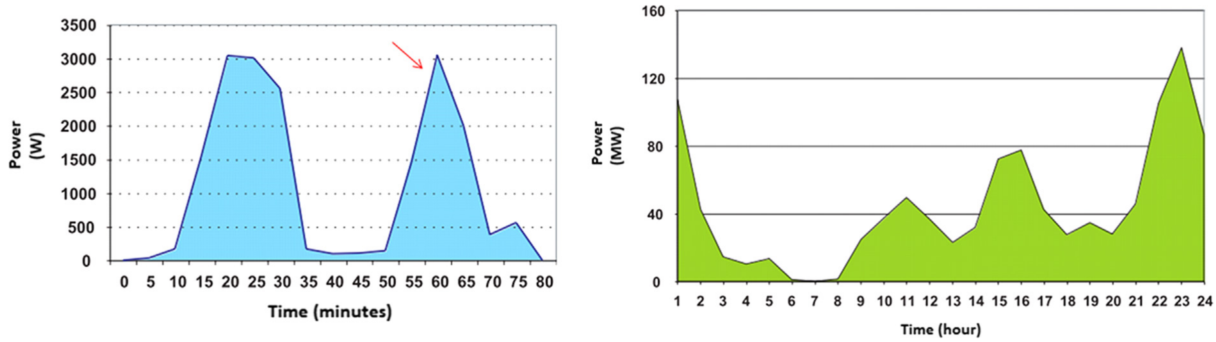


Fig. 7. Typical working cycle of a dishwasher and average daily pattern of use [19].

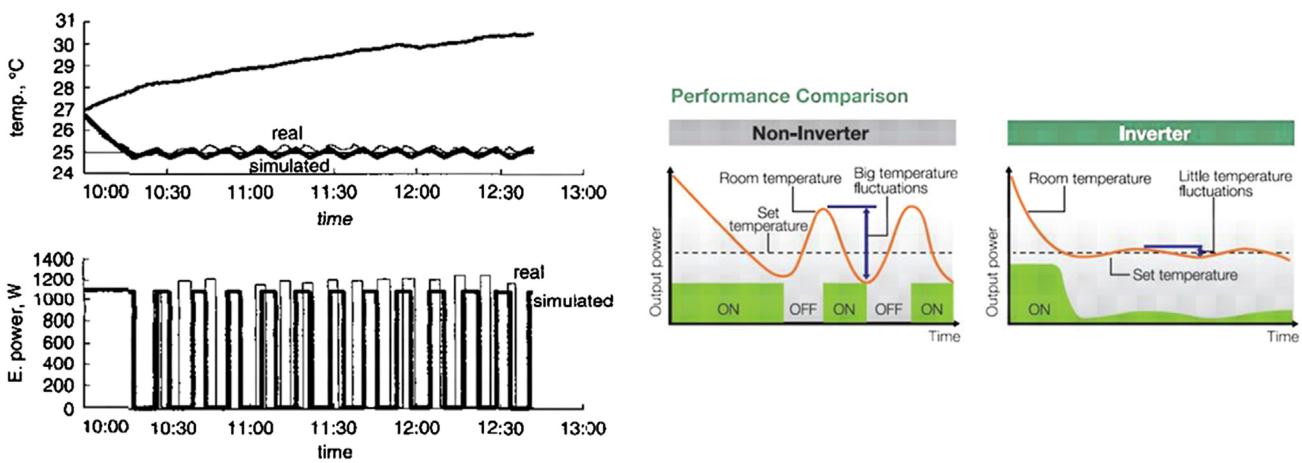


Fig. 8. Temperature variation and typical working cycle of an air conditioning system [40–42].

The main objective of an air conditioning systems is to provide thermal comfort to the user [39] and the main difficulty associated with this type of load is the correct regulation of the temperature when aiming to save energy (Fig. 8). Due to the energy storage capacity existing in rooms being heated/cooled, a direct load control action is possible over this load aiming at re-shaping the system peak load profile and, in this way, the shape of the load diagram [39].

Most energy used in an air conditioning system (in the cooling function) in the refrigeration cycle is for compressing the refrigerant and transfer indoor heat outdoors, and it can increase or decrease depending on weather conditions and indoor heat load.

Nonetheless, actions to manage these type of systems, either the re-set of thermostat parameters or short time interruptions must assure thermal comfort to the end-user [39] without neglecting the payback effect [29,40,43,44].

4. Load categorization

Residential loads have been mainly seen as passive devices that consume energy [35]. However, the way appliances are seen is changing and their contribution to the electricity consumption can be somehow managed, aiming at reducing it during specific periods of time, decreasing electricity bill and contributing to maximize the integration of renewables [21,35].

The partial control of demand is possible since the end-users need for energy services may be not coincident with electricity consumption. Summing up the previous section it is possible to conclude that:

- in some end-use loads, usually thermostatically loads, there is a certain dissociation between energy services provided and electricity consumption, like electric water heaters;
- the level of some energy services can be slightly changed during short periods of time leading to changes in the energy consumption without noticeable changes in the quality of the energy service provided (cold appliances, air conditioners and electric water heaters);
- the normal functioning of some end-use loads can be interrupted during short periods of time without decreasing of the energy service provided (cold appliances, air conditioners and electric water heaters);
- some energy services may be provided in different periods of the day when there are economic advantages for the end-user without decreasing their quality (washing machines, dishwashers, clothes dryers) [45,46].

Therefore, some control over these domestic loads is allowed through smart ADR actions implemented by using an EMS endowed with adequate algorithms [47]. It is important to enhance that these ADR actions must be tailored to each one of the controllable loads, respecting therefore technical constraints, and must be adapted in order to respect end-users' preferences and achieve their objectives (e.g. reduce electricity bill or maximizing the use of renewables).

According to the previous section, in which some typical patterns of usage and technical constraints have been presented, it is possible to classify loads into four main categories according to the degree/type of control [48]:

1. non-controllable loads: loads that when controlled may cause discomfort to the user or perturbation to ongoing activities (lighting, office and entertainment equipment, cooking appliances);
2. reparameterizable loads: loads that are thermostatically controlled and allow a re-set of thermostat settings without causing discomfort to the user (cold appliances, air conditioning systems and electric water heaters);
3. interruptible loads: loads that can be interrupted during a short period of time without decreasing the quality of the energy services provided (cold appliances, air conditioning systems and electric water heaters);
4. shiftable loads: loads whose functioning can be postponed or anticipated according to end-users' preferences but without bringing discomfort (washing machines, clothes dryers, dishwashers and electric water heaters).

In Fig. 9 the potential of controllable demand is represented by the loads that can be shifted plus interruptible and reparameterizable loads (which already include cold appliances). However, this potential does neither include air conditioning systems nor electric water heaters since the categorization was based on data [19]

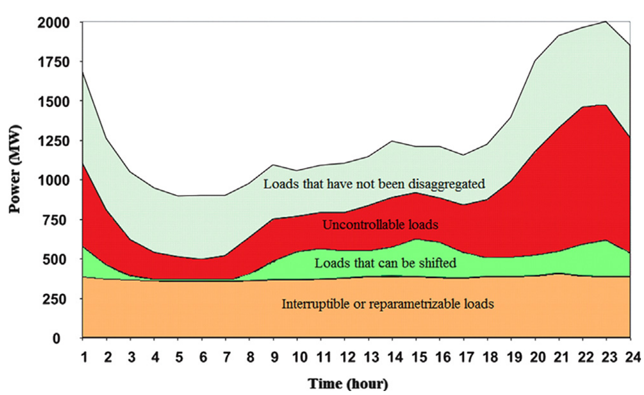


Fig. 9. Load categorization.

that did not distinguish those loads. This way, the potential of controllable loads is even higher than it is presented in Fig. 9.

According to this categorization, and the typical annual consumption of those loads in Portugal, it is possible to depict a chart (Fig. 10) displaying the degree of load control and annual electricity consumption:

- the x-axis is the annual electricity consumption (GWh);
- the y-axis is the load's degree of control;
- the circle or/and the ellipse represent all the possible types of control, being the most typical control represented by the circle;
- each round circle has a size proportional to the average electricity consumption per year.

Fig. 11 provides information on the loads that have higher annual electricity consumption and also those that may be the target for more than one type of control action.

It is important to point out that although the same type of control may be applied to several loads, the characteristics of those control actions (interruption duration, temperature parameters, time deferral, etc.) are different and may also differ along the day. This means that each control strategy must be tailored to each end-use and must therefore take into consideration the energy service to be provided.

The loads that present higher annual consumption are fridges, air heating systems and freezers. Fridges and freezers are appliances that are always on during all day and therefore their high annual electricity consumption is justified [49]. Air heating, despite the seasonality of its use, also has high electricity consumption and one of the reasons may be the poor insulation in buildings together with the high ownership rate of these systems.

As far as control is concerned, electric water heating systems may suffer different actions: they can have the temperature re-set, be interrupted and even have some flexibility in terms of schedule, as long as water is hot at a certain hour. Also fridges and freezers may be interrupted during a short time period and can also have the temperature re-set. These different actions to be applied are represented in Fig. 10 using ellipses that cover different possible types of control. Ovens, lighting, office and entertainment equipment cannot be managed, since their control may interfere with end-users' comfort and activities thus depreciating the quality of the energy service provided.

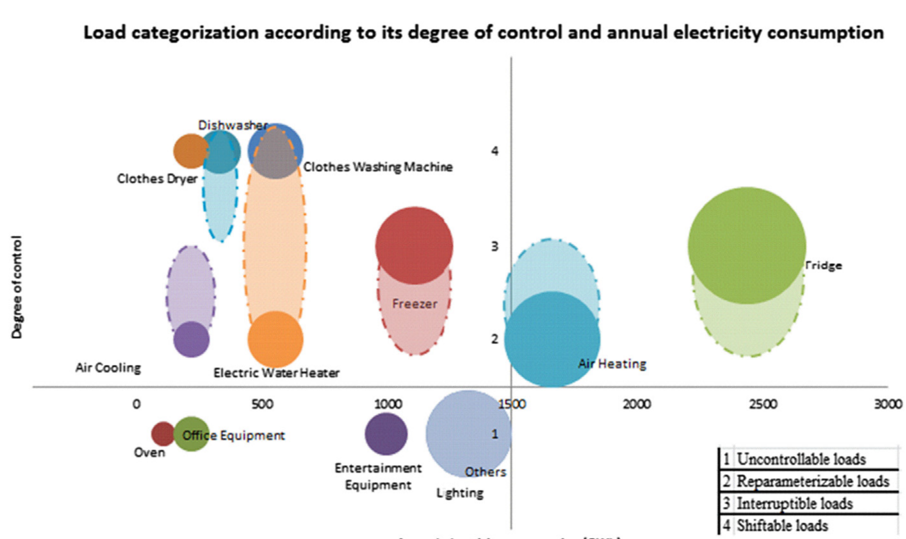


Fig. 10. Load categorization according to its degree of control and annual electricity consumption [49].

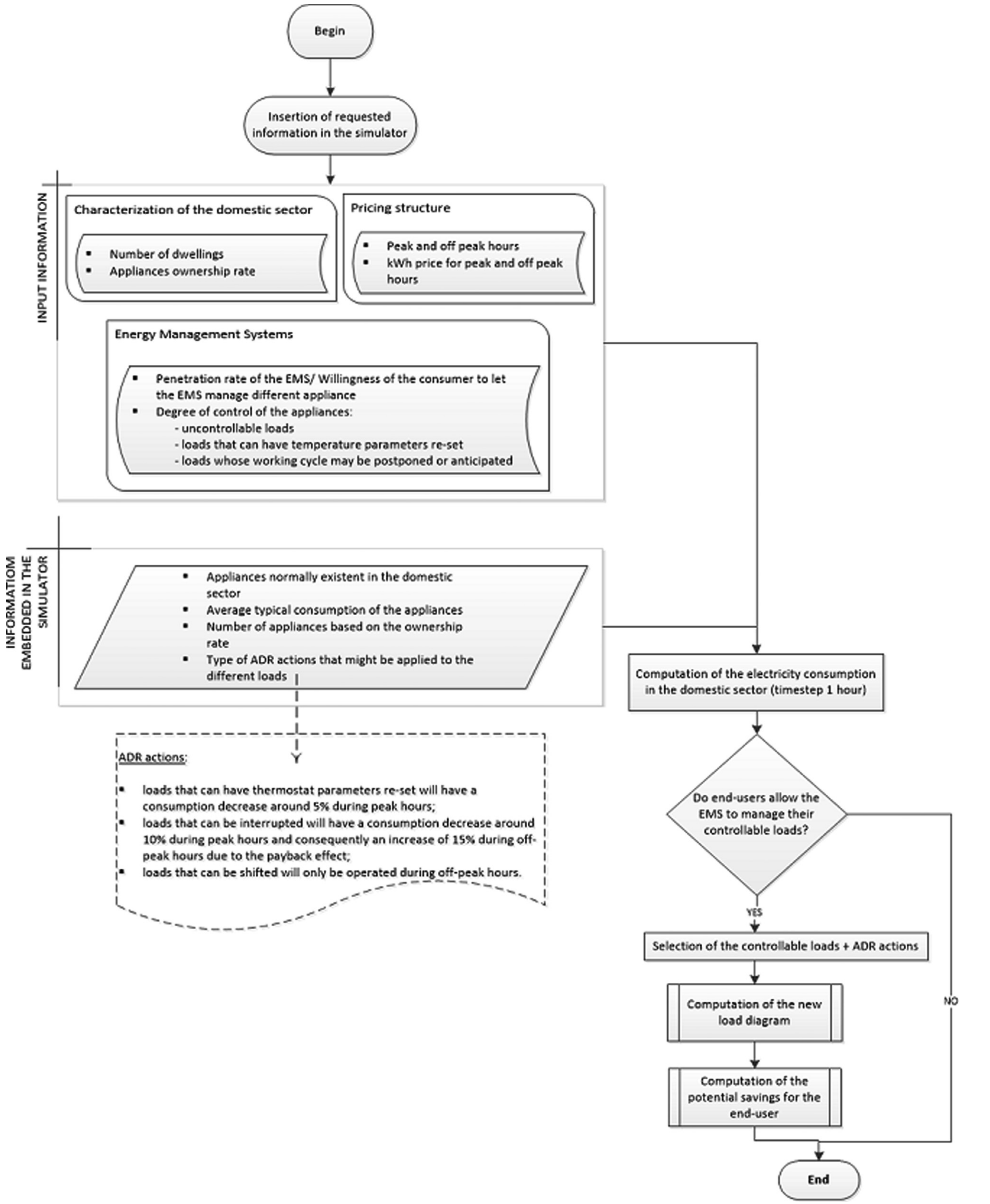


Fig. 11. Process implemented to assess the impacts of ADR actions.

Analyzing the manageable demand and the information available in Fig. 2, it is possible to estimate the potential to manage these loads, although with different types of control, in up to 60% of the annual electricity consumption: about 10% can be deferred in time and 50% can be interrupted during short periods of time or have the parameters re-set. This does not mean that the savings

can achieve 60% of the annual electricity consumption, but that 60% of that consumption can be the target of demand response actions.

5. Results – impact on residential load diagram due to the use of EMS

A model has been developed to assess the impacts on household load diagram originated by the use of an EMS able to:

- shift the consumption of dishwashers, washing machines and clothes dryers;
- set new thermostat parameters on fridges, freezers, electric water heaters and air conditioning systems.

The objective of this model is to reproduce some of the measures previously mentioned and assess the impacts on the national load diagram, as well as the economic savings for the typical household end-user.

Despite the uncertainty and the variability of the electricity consumption of each domestic end-use load associated with the family composition, habits and preferences [50], the fact that most houses have a common portfolio of appliances (refrigerators, washing machines, dishwashers, etc.) allows to establish similar electricity reduction strategies and assess their impact [46] considering the potentially controllable demand and the flexibility in load usage.

The model developed to reproduce household electricity consumption is based on input information such as:

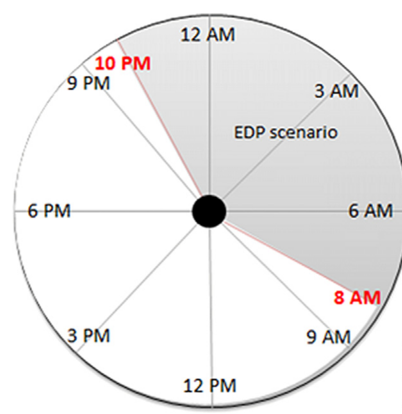
- number of dwellings;
- peak and off peak hours (i.e. pricing structure);
- appliances ownership rate;
- average typical consumption profile of the appliances;
- penetration rate of the EMS;
- willingness of the end-user to let the EMS manage different appliances;
- degree of control of those appliances:
  - uncontrollable loads;
  - loads that can have the temperature parameters re-set;
  - loads whose usage can be postponed or anticipated.

Also some assumptions have been made in order to control the loads characterized in Section 3 according to their degree of control and foresee some of the possible impacts on the average daily load diagram:

- loads that can have thermostat parameters re-set will have a consumption decrease around 5% during peak hours;
- loads that can be interrupted will have a consumption decrease around 10% during peak hours and consequently an increase of 15% during off-peak hours due to the payback effect;
- loads that can be shifted will only be operated during off-peak hours.

With this information, the tool is able to calculate the number of appliances in the residential sector, their consumption profile and compute the new load diagram (Fig. 11). According to the rate of penetration of integrated EMS, represented by a percentage at the left side of the load diagram (Fig. 12), the multiple impacts on the load diagram are perceived. Different case studies regarding the penetration of EMS and load management actions are assessed. Fig. 12 is the base scenario and shows the residential load diagram when there are no management actions implemented (0% penetration rate of EMS). According to this base scenario it is clearly identifiable a power peak around 11 pm and a valley between 2 am and 9 am.

Considering now the case study I in which a two-rate time-of-day tariff is considered with off-peak hours between 10 pm and 8 am (Fig. 13) and allowing the EMS to manage the end-use loads with two different penetration rates (70% and 100%), it is possible to foresee the impacts on the residential load diagram (Fig. 14).



	kWh price(€)
Off peak hours	0,095694
Peak hours	0,178104

Fig. 13. Case study I – peak and off-peak hours and corresponding prices.

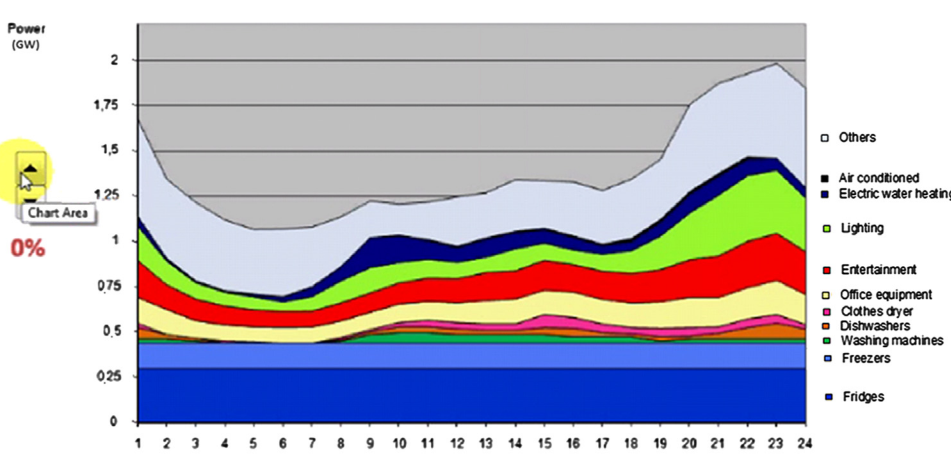


Fig. 12. Base scenario with no management actions implemented.

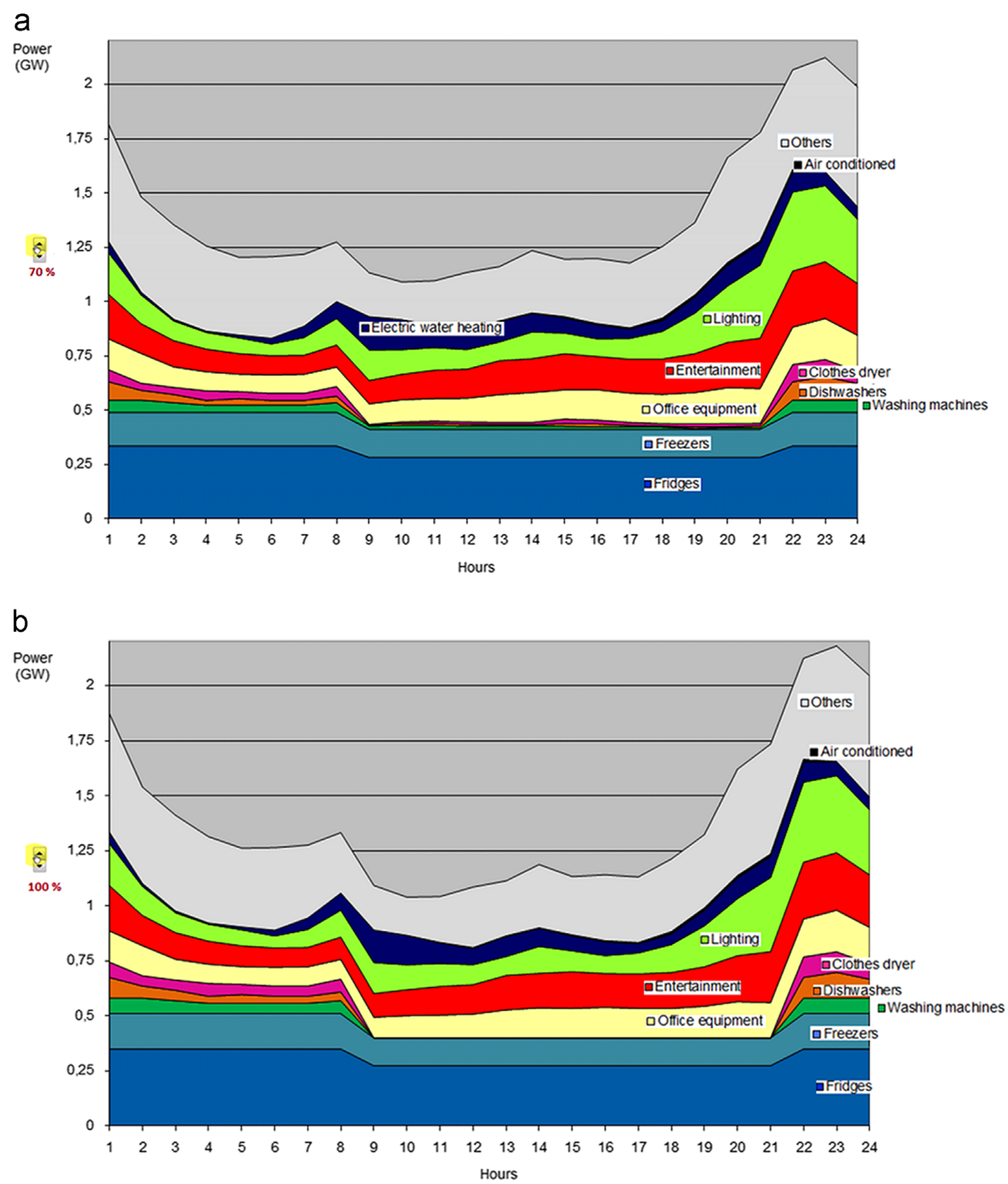


Fig. 14. Case study I – possible impacts on load diagram considering the penetration rate of EMS (70% and 100%).

Although there is a shift in consumption from peak hours to off peak hours and a decrease of the consumption of thermostatically controlled loads, there is an increase of consumption around 11 pm and a decrease of consumption between 8 am and 8 pm, when comparing this scenario to the base scenario (Fig. 12).

Considering dynamic prices, the benefits to the end-user that uses an EMS can be maximized. Grouping the end-use loads in two groups (loads that can be shifted and thermostatically controlled loads) and assuming different percentages for the end-user's willingness to let the EMS manage those loads, different percentages of savings can be achieved with a maximum of 3% (Fig. 15).

Adjusting now a new scenario (case study II) with off-peak hours between 2 am and 8 am (Fig. 16) and allowing the EMS to manage the end-use loads with the same previous penetration rates (70% and 100%), it is possible to see that the peak demand is considerably reduced and the load diagram smoothed (Fig. 17).

Although several studies considering direct and indirect feedback report savings in a range from 5% to 15% and 0% to 10%, respectively [51], this tool points out about 5% of savings for the typical residential end-user in Portugal in this new scenario.

Even though this saving percentage is low when compared to other studies, the fact that it does not depend on direct action of end-users is a major advantage. The savings originated by direct feedback with displays that show the instantaneous and accumulated demand depend on the end-user behavior and the frequency that the end-users look at the displays, which is likely to decrease over time. The savings presented here only depend on the automated EMS and the willingness of the end-user to let this hand-off system manage his/her appliances (Fig. 18).

Another case study (case study III) is the assignment of different willingness percentages to the end-uses loads [49]. This captures the fact that different end-users will have different reactions considering the set of manageable loads. Considering the “percentage of willingness” presented in Table 1, the impacts on the load diagram with peak and off-peak hours from case study II (Fig. 19) are significantly different from the previous case studies.

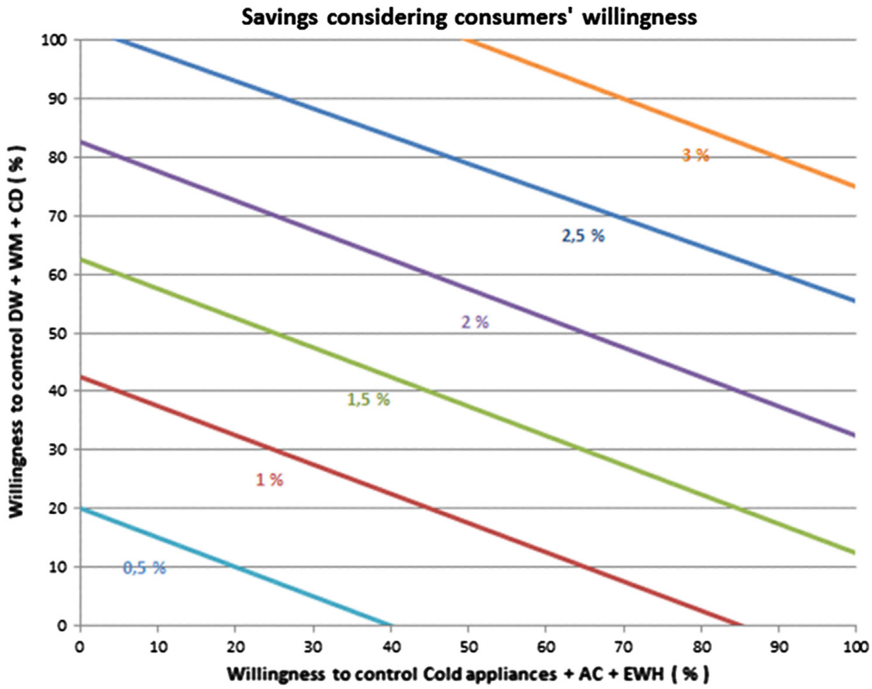


Fig. 15. Case study I – savings considering end-users' willingness to let the EMS control different types of appliances (dishwashers + washing machines + clothes dryers and thermostatically controlled appliances).

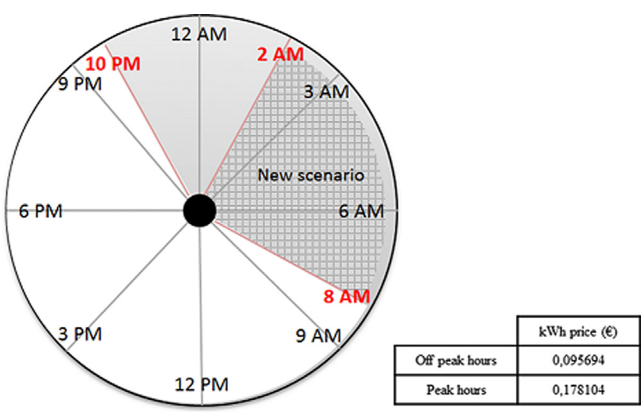


Fig. 16. Case study II – off-peak hours for the new scenario and corresponding prices.

When comparing this case to the case study II with an EMS penetration rate of 70%, the reduction of the peak consumption is similar and the consumption during the valley is slightly higher. This shows that different percentages for different appliances will have different impacts on the residential load diagram.

6. Energy management systems

The operation of the electricity system has traditionally consisted of a load-following operating strategy, first estimating the expected demand and, based on this estimation, finding the best supply-side options to meet demand while assuming that electricity demand is almost inelastic [45,53].

Under the present traditional tariff structure, most end-users are billed in a monthly basis for the total amount of used electricity [46,54], without seeing truly hourly variations in the price of electricity and, therefore, with little incentive to change their behavior. In the smart grids context, due to the expected kWh price variation, electricity consumption decisions would certainly be different and so would the consumption pattern. Emerging Smart Grids will provide residential end-users' the possibility to monitor electricity prices and control their electricity use according to those price signals [55] thus increasing the price elasticity of demand that nowadays is usually found to be almost inelastic [56]. To achieve that aim, part of the domestic demand, as presented in Section 3, may be treated as a manageable resource and a more active and flexible participation from the end-users regarding their electricity consumption is expected [7,24,57]. However, for this behavior change induced by price variations, end-users must receive adequate signals [51], such as time varying prices, and have a hands-off system endowed with optimization algorithms to automatically manage their consumption [58]. The deployment of EMS, which can automatically shift a portion of the end-users' demand from periods of higher prices to periods of lower prices and allow maximizing the integration of local generation and storage, will give Demand-Response schemes a more important role in the electricity market.

This reappearance of demand responsive programs is thus supported by the clear need to manage load operation in order to benefit from variable tariffs and renewables availability [16,22,59] and also from their potential contribution to increase reliability, decrease generation shortfalls and transmission congestion as well as drop of financial risks such as wholesale price spikes [60]. These programs and actions should, however, be carefully designed to induce acceptance and avoid undesirable effects such as the payback effect [61] and the reduction of quality of the energy services provided. Thus the previous characterization of manageable energy resources and assessment of the potential effect of ADR actions in the domestic load diagram is of utmost importance.

Several studies developed by different authors already focus on the control of different appliances, mainly thermostatically controlled loads like air conditioning systems and electric water heaters [24,28,29,54,62–65]. Nonetheless, more loads and

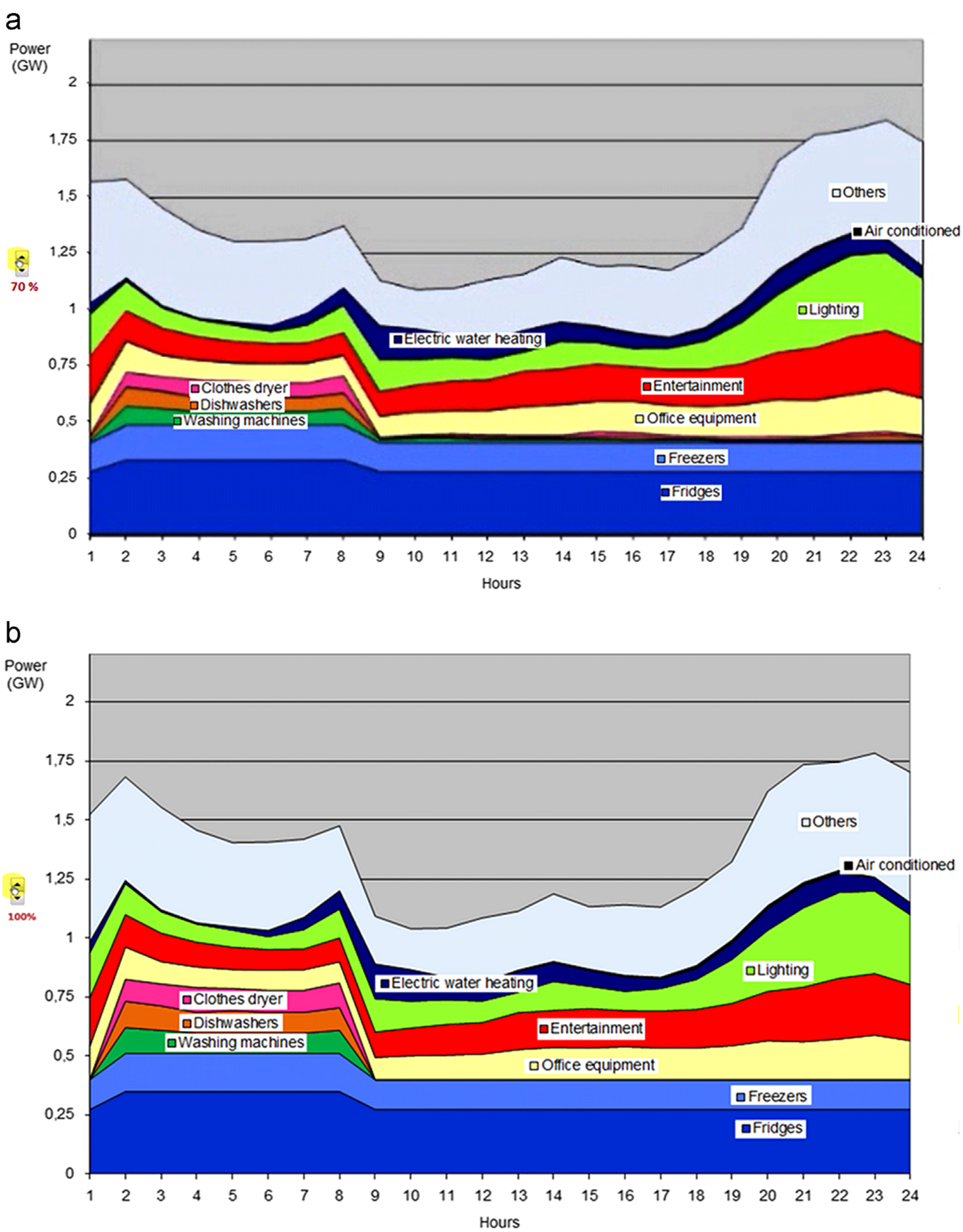


Fig. 17. Case study II – possible impacts on load diagram considering the penetration rate of EMS according to the new scenario [48].

appliances in the residential sector besides air conditioning and electric hot water heaters may be appropriately managed in order to maximize the demand available for control. The Energy Box concept was initially proposed as a “24/7 background processor able to manage one's home or small business electrical energy usage hour-by-hour and even minute-by-minute” [66]. The aim of the development of the Energy Box and its algorithms is to coordinate the electricity demand, energy storage, local generation and selling back to the grid according to price signals, comfort requirements, weather conditions and renewable availability. The Energy Box intends to exploit the flexibility that end-users generally have in the timing of their electricity usage to induce changes in their electricity-consuming patterns to achieve an overall optimal system control through time-varying electricity pricing.

The major differences between the research already done by other authors and our research lay on the demand response actions applied to different groups of loads categorized according to the type of control aiming at an optimized management of the residential energy resources and the previous assessment of the impacts on the domestic load diagram caused by the use of EMS.

The final aim of our work is to develop a methodology to jointly schedule and/or change the working cycles of several appliances, manage energy storage systems and decide on consumption, selling or storage of energy produced by micro-generation systems, based on this characterization of controllable demand and the assessment of the impact of implementing several actions with different rates of penetration of EMS. The approach under development incorporates adequate algorithms, namely based on operations research techniques for decision support [47], to

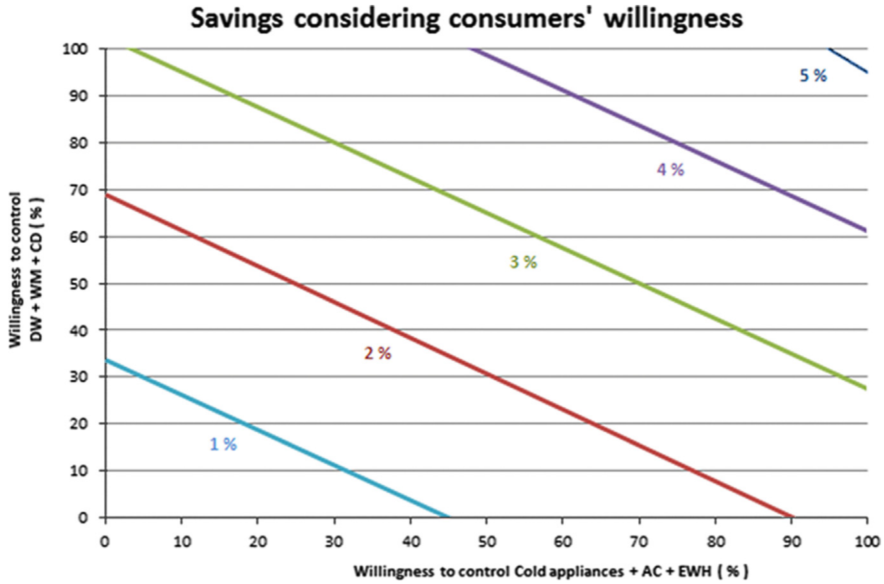


Fig. 18. Case study II – savings considering end-users' willingness to let the EMS control different types of appliances (dishwashers+washing machines+clothes dryers and thermostatically controlled appliances) according the new scenario [52].

Table 1
Case study III – willingness of end-users to let end-use loads be managed.

End-use loads	Willingness (%)
Fridges	70
Freezers	70
Washing machines	40
Clothes dryers	40
Dishwashers	90
Electric water heaters	90
Air conditioning systems	100

produce learning and adaptive energy management strategies that have the capability to address usability and interests from the end-users' perspective, namely regarding reducing costs, while:

- guaranteeing quality of energy services;
- satisfying users' preferences;
- optimizing the use of endogenous resources.

7. Conclusions

The evolution of the traditional grid towards smart grids will enable the development of new strategies aiming at an optimal management and control of the electricity grid. Additionally, changes in the architecture and technologies used to monitor and control the electricity consumption and infrastructure are required in order to manage distributed energy sources, energy storage systems and residential controllable loads. With these technologies, electricity end-users may become responsive customers and economically motivated users who not only consume but also produce and make an active management of electricity storage and consumption [25], allowing them to have a more active role in the energy market [67].

The existence of prices of electricity that can vary frequently and significantly in magnitude coupled with automated EMS will allow the end-user to respond intelligently to price signals and will induce savings for the end-user through an optimized use of his/her energy resources. If many end-users respond to these signals changing their consumption, it will cause demand redistribution away from the current peaks. The final result has advantages from different perspectives:

- economic incentives and reduced electricity bill for the individual end-user who is able to decrease costs by performing a smart management of electricity consumption, storage systems and micro-generation;
- to the society by deferring the demand for new generation and decreasing environmental impacts;
- to the different power system sector players, including retailers, that can see their profits increasing [68,69].

It is important to highlight that the typical end-user does not have all required knowledge or even time to optimize his/her electricity consumption given the multiplicity of decision parameters and constraints involved and their possible variation over time [1]. The use of time-of-use tariffs with a higher number of rates will provide more stimuli for smart management of resources but will increase the complexity of management. Therefore, it is necessary to develop management systems with adequate algorithms aiming to optimize the integrated use of all resources. A domestic EMS in a smart grid context, with the main goal to reduce end-user's electricity bill, will involve making decisions based on price information, the possibility to postpone or anticipate load operation and the ability to produce, consume, sell or store energy [1], while respecting users' preferences [70].

The characterization of household electricity consumption presented in this work is a crucial step in order to do an adequate load categorization of end-use loads according to their degree of control or availability to be the target of management actions, enabling the identification of controllable demand. Also a tool has been developed to assess the impact on the load diagram caused by the deployment of EMS.

The fact that the load diagram suffers different impacts considering distinct tariff period schemes, even with the same kWh price, shows the importance to adequately assess scenarios with diverse tariff period definitions and electricity prices. This price and hour distribution should be analyzed trying to conciliate the different perspectives: one aiming to maximize utilities' profits plus minimizing system operational costs, and the other one with the objective to minimize the residential end-users' bill.

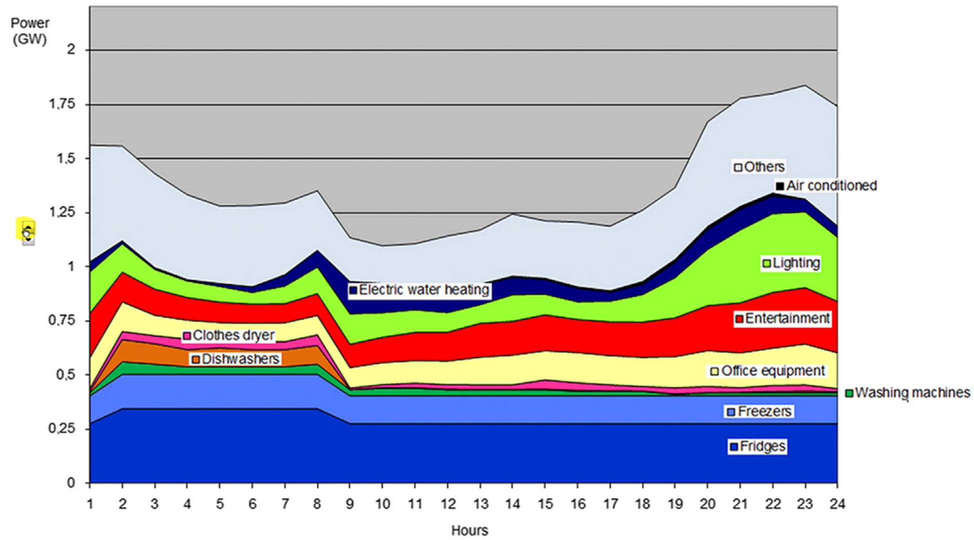


Fig. 19. Case study III – possible impacts on load diagram considering different percentages for different end-use loads.

According to the case studies presented in this paper, different penetration rates of the EMS and/or different percentage of willingness to let the EMS manage different end-use loads would generate different savings and have different impacts on the residential load diagram. The scenarios analyzed in this paper show that savings can vary from 0.5% up to 5%. Due to the deferral of electricity consumption it is possible to achieve the reduction of peaks in the residential load diagram and also a flatter valley. These results are the foundation for the design of demand response algorithms to be implemented in an EMS able to achieve an overall optimization of all energy resources. Work currently underway includes the use of genetic algorithms to cope with complex combinatorial optimization problems [47] and agent-based models to simulate the electricity consumption of end-use loads and end-users' behavior also comprising storage and microgeneration systems since their use will increase the number of decisions and their complexity.

Acknowledgments

This work has been framed under the Energy for Sustainability Initiative of the University of Coimbra and supported by Energy and Mobility for Sustainable Regions Project CENTRO-07-0224-FEDER-002004 and Fundação para a Ciência e a Tecnologia (FCT) under Grant SFRH/BD/88127/2012, and Project Grants MIT/SET/0018/2009 and PEst-C/EEI/UI0308/2011.

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